Deployment of the MARSIS Radar Antennas

On-board Mars Express

M. Denis* A. Moorhouse.†, A. Smith‡, M. McKay.§
European Space Agency, ESOC, Darmstadt, Germany

J. Fischer**, P. Jayaraman††, Z. Mounzer‡‡,
VEGA, Darmstadt, Germany

R. Schmidt§§, J. Reddy***,
European Space Agency, ESTEC, Noordwijk, The Netherlands

E. Ecale†††,
EADS Astrium, Toulouse France

R. Horttor‡‡‡, D. Adams§§§,
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

and

E. Flamini****
Italian Space Agency, Rome, Italy

On the first European planetary mission, the deployment of the two 20-meter long MARSIS antennas onboard the ESA Mars Express spacecraft has represented an unprecedented technological challenge, in the middle of a successful science mission. While Mars Express was already performing regular observations at Mars, a complex process has been performed on Earth, involving the ESA Project, coordination between ESA, NASA and ASI, the Mars Science community, the spacecraft manufacturer EADS Astrium and the Mission Control Centre at ESOC. This paper describes the steps that led from an initial no-go in 2004 to deployment one year later, as well as the conditions and difficulties encountered during the actual deployment. It provides insights in the technical and managerial processes that made it a success, and analyses the rationale behind the decisions.

* Mars Express Mission Operations Manager, Operations Department.
† Mars Express Deputy Spacecraft Operations Manager, Operations Department.
‡ Head of the Flight Operations Division and Mars Express Flight Operations Director, Operations Department.
§ Mars Express Ground Segment Manager and Deputy Flight Operations Director, Operations Department.
** Mars Express Attitude and Orbit Control Operations Engineer, Operations Department.
†† Mars Express Attitude and Orbit Control Operations Engineer, Operations Department.
‡‡ Mars Express Data and System Operations Engineer, Operations Department.
§§ Mars Express Project Manager, Science Projects Department.
***tbd.
††† tbd.
‡‡‡ Mars Express - NASA Project Manager.
§§§ Senior Engineer, NASA's Jet Propulsion Laboratory.
**** tbd

Nomenclature (to be included)

MARSIS = Mars Advanced Radar for Subsurface and Ionospheric Sounding

I. Introduction

<copied from the Abstract, to be streamlined>

One radar at Mars, two 20-meter long "jacks-in-the-box", three critical deployments in the middle of a successful mission: In the frame of the first European planetary mission, the deployment of the MARSIS antennas onboard the ESA Mars Express spacecraft has been itself a dedicated mission. While Mars Express was already performing regular observations at Mars, a complex process has been performed on Earth, involving the ESA Project, coordination between ESA, NASA and ASI, the Mars Science community, the spacecraft manufacturer EADS Astrium and the Mission Control Centre at ESOC.

JPL, provider of the antenna booms for the Italian instrument MARSIS, called off the deployment in April 2004, due to a newly identified risk of a boom hitting the spacecraft. Further mechanical studies and simulations took months due to the complexity of this non-deterministic problem. In parallel, finding a new deployment window had to perform a trade-off between operational constraints and science requirements of the teams who wanted to minimize the impact on the scientific coverage. Meanwhile, the MARSIS team was eager to deploy as soon as possible.

A GO for deployment was reached only in 2005. Risk analyses recommended safing measures to minimize potential impact on vital spacecraft elements and to verify its health and configuration after the deployment of each boom, which vastly increased the operational complexity. A simulations campaign in April 2005 prepared the mission team for these critical operations, while a flight pre-deployment test campaign was executed in the gaps not used by the science mission.

The first deployment firing occurred successfully on May 4th, 2005. During the subsequent precise spacecraft dynamics characterization, it was discovered that the 20-meter boom was not fully extended but bent at two thirds of its length. A strategy was developed to obtain full deployment of the boom, which was achieved thanks to a controlled warming-up by the Sun of the problematic hinge. However, this unexpected failure mode could have occurred on hinges closer to the spacecraft, which may have resulted in loss of controllability and danger to the mission.

Operations management had to trade-off between resuming the mission, antenna half-deployed and without MARSIS, on robust but inaccurate attitude controllers, or taking the risk to deploy the second long boom. At this time, and unrelated to MARSIS, a minor wheel electronics glitch occurred, during the recovery of which the spacecraft ended up on thruster control, with such poor pointing performance that communications with the spacecraft were not reliable. The anomaly was fixed "in the blind" and good communications recovered. It was decided to continue. The second 20-meter boom was successfully deployed on June 14th; the third boom, only seven meters long, on June 17th 2005. All fully extended!

II. Project History (1998-2004): A Radar At Mars, Why And How

This chapter describes the design and time logic that flows from the science objectives of Mars Express and Marsis to the solutions retained for constructing, mounting and deploying the booms.

A. Why Marsis On-Board Mars Express

Rudi, John?

B. Marsis Science Objectives Summary

Enrico?

C. Antenna Design and Validation of the Deployment on Earth

The MARSIS antenna faced a serious design challenge: namely to produce a 40 m dipole and a 7 m monopole that fit within a modest stored volume, a tight mass constraint, and when deployed would exhibit a first mode natural frequency of at least 0.05 Hz. The solution was a tubular structure made of fiber glass layers and Kevlar composites. The dipole booms were each 20 m long and 3.8 cm in diameter. The monopole was 7 m long and 2.0 cm in diameter. The tubes were folded into 1.5 m segments at 13 hinge points made of cut outs in the tube walls. Each dipole boom was folded into a volume of about half of its uncompressed state. The resulting compressed stored energy was to become a major driver for the deployment dynamics.

The spacecraft designers worried about two mechanical aspects of the antenna. One was the tip off transient at initial deployment where the concern was dynamic shock to the spacecraft. A finite element model developed by the antenna manufacturer, Northrop Grumman - Astro Aerospace, produced the predicted shock spectrum. Spacecraft dynamics experts determined there was no threat. The second worry was the deployed natural frequency which had to be greater than 0.05 Hz in order to not interfere with spacecraft attitude control. The aforementioned finite element model together with vibration tests produced an answer of about 0.08 Hz. However, it took about a year and a half to resolve the residual concerns given the criticality of this parameter.

Meanwhile, no one worried about the approximately one minute of the actual deployment transient. Each 20 m boom had mass of 1-kg. The structure was so large and light, there was no real way to test it in Earth gravity and atmosphere. Astro Aerospace developed a simulation program to model the deployment transient. The result appeared sufficiently benign that no one actually questioned the validity of the model. In April 2004, while working with a deployment simulation of the antenna for the SHARAD instrument (SHAllow RADar, an instrument on NASA's Mars Reconnaissance Orbiter), an error in the way damping was modeled in the software was discovered. When corrections were made to the MARSIS deployment model, the results were highly chaotic and so different from the previous results that proceeding with MARSIS deployment at that time would have been irresponsible. The Mars Express-NASA Project Manager notified ESA of the need to postpone the scheduled deployment. As it happened, this realization and notification took place a mere 12 hours before ESA was to load the deployment sequence aboard the spacecraft.

The expected science value was such the deployment was very desirable. JPL spent the next four weeks attempting to identify and solve the problems. At a review with ESTEC on May 14, 2004, it became apparent that too little was actually known about the real deployment expectations and the mechanical properties to proceed. JPL then put together what amounted to a retroactive qualification effort, considering the flight article was already at Mars and only the Engineering Model was available to test. This effort will be described later.

D. Spacecraft Constraints

Eric?

Impact on the SC attitude control during and after the deployment; resulting attitude controllers for the whole deployment phase.

Initial risk assessment

Basic requirements for characterization of the deployment

E. Operations and Commissioning Constraints

Alan M.?

(also include the trade-off on the deployment target date as early / as late as possible: science demo phase for the optical instruments just after Mars arrival, concerns of the other PIs, maximum eclipse duration…)

III. Final Preparation (2004-2005): To Deploy or Not to Deploy

This chapter describes the eventful phase which transformed a No-GO in April 2004 into a Go in April 2005.

A. Overall Management and Responsibilities

Rudi, John?

B. The Point of View of the Marsis Principal Investigator

Enrico??

C. Boom Deployment Studies

One of the key issues with a lightweight, large motion, and highly dynamic deployment such as MARSIS is that friction, gravity, and aerodynamic resistance forces will dominate any attempts at ground based testing. The boom is extremely light weight and its properties are also temperature dependent. As a result of the influence of these forces it impossible to test the full system behavior prior to flight and we must rely on analysis to predict the deployment dynamics. Due to the infeasibility of a full system test, a computational study was used to determine the critical controlling parameters of the deployment which resulted in narrowing the planned component testing to three major parameters: the hinge buckling strength, the hinge torque profile, and the stowed compressive energy.

The hinge buckling strength was measured using sections of the flight spare boom in a four-point bending fixture. Results from this test indicated that the in-situ hinge strength of the flight booms was lower than previous measurements had suggested and that buckling could occur both in the hinge section and in the material immediately adjacent to the hinges. Additionally, the hinge deployment torque was measured in an environmental chamber at its on-orbit temperature of -70 C to better characterize its contribution to the deployment energy as well as the hysteresis energy dissipation associated with any hinge buckling events. Finally, the stowed energy due to the compression of the tube diameter in the cradle was measured in a vacuum chamber at -70 C for all three booms.

The boom deployments were simulated using a highly specialized ADAMS model. The model was constructed with 13 straight segments connected by spline hinge joints that reproduced the measured hinge torque profile and buckling strengths. Each of the 13 straight segments was composed of two beam elements that employed an automated algorithm to update the structural (stiffness proportional Rayleigh) damping parameter based on the local straight section beam length and end conditions. Finally, the accordion style stowed state was modeled with gap springs connecting adjacent boom segments in order to capture the stowed compressive energy.

A total of 1000 cases of the ADAMS model were run in a Monte Carlo study of the deployment dynamics. One of the key results from the Monte Carlo analysis was the discovery that a number of scenarios were possible that could result in the boom re-contacting the spacecraft during the deployment. Due to the high compressive energy the dipole boom reaches its full 20 m length in about 2.5 seconds, after which, it typically experiences a "whip" type behavior and tends to fold back towards the spacecraft in two or more sections. The margin against boom re-contact was quantified based on the closest buckled hinge after the full length of the boom was reached and it was exhibiting recoiling motion.

Results from the Monte Carlo study indicated that there was a significant probability that the MARSIS booms could contact the spacecraft or solar arrays during the deployment. Based on this result, a failure modes analysis was done at ESA using the energies and incidence angles obtained from the Monte Carlo runs. The conclusion of this analysis was that, while significant damage to the spacecraft was possible, the likelihood of it occurring was very low. Hence, the decision was made to proceed with the deployment.

D. Spacecraft Protection Strategy

Eric?

E. Operations Coordination and In-flight Tests

Alan M.?

F. Operational Timeline Preparation

Zeina?

G. Preparation and Verification of Attitude Control Products

Jay, Joerg??

IV. The Deployment and Its Surprises (May-June 2005)

A. Overall Execution Conditions
Michel / Alan M.?
(usage of MCR, shifts, organization)

B. The First Boom: An Excellent Spacecraft Behavior
Eric

C. The First Boom : an Unexpected Behavior

Having spent a year working the technical issues involved in deployment, the ESA/NASA JPL/EADS Astrium team approached the scheduled May 4, 2005 deployment with enthusiasm and confidence. At first impression of the event, deployment appeared successful. There was a significant tip off motion of the spacecraft, followed by jerky motions of the dynamics, concluding with a damped sinusoidal behavior. Champagne time at ESOC!

However, detailed analysis of the flight telemetry showed a total of three clearly observable frequencies at 0.043 Hz and 0.146 Hz about one axis and the third at 0.076 Hz about the other axis instead of the expected pair of frequencies near 0.10 Hz. These measured frequencies were completely unexpected. The moments of inertia data for the spacecraft also were not consistent with a single segment boom. The anomalous inertia cross-product values and the smaller than expected principal axis values suggested a partial deployment with a "bent" end. Both the frequency and inertial data were consistent with the 10^{th} hinge from the spacecraft being stalled at a 40° angle. An "even" numbered hinge would have been colder than an "odd" numbered hinge and would have been pre-bent away from the sun direction.

Test data taken months before on the hinge torque versus angle characteristic at very cold temperature showed a small region of negative torque at about 40°! If the boom deployment energy had reached zero with the boom segment bent greater than 40° deg at hinge-10, the segment could easily remain "stuck". Thus a 40° partially deployed hinge-10 was the likely condition. As it happened, the sun angle at that hinge was such that it gave the least possible warming , thus adding strength to the theory.

D. Stop or Go?
Alan S.

E. How to Unbend The First Boom
Mike.

F. A Minor Anomaly and its Drastic Consequences
AOCS Acquisition Control Board (ACM-B) Telemetry wraparound.
Alan M..

G. The Second Boom Deployment
Michel

H. The Monopole
Joerg.

V. Conclusion

Michel and others

Appendix

<needed ?>.

Acknowledgments

The authors thank
<whoever we want to thank >.

References

Periodicals
<any? >

Books
<any? >

Proceedings
<any? >

Reports, Theses, and Individual Papers
<any? >

Electronic Publications
<any? >

Computer Software
<any? >

Private Communications and Web Sites
References to private communications and personal Web site addresses are generally not permitted. Private communications can be defined as privately held unpublished letters or notes or conversations between an author and one or more individuals. They *may* be cited as references in some case studies, but only with permission of the AIAA staff. Depending on the circumstances, private communications and Web site addresses may be incorporated into the main text of a manuscript or may appear in footnotes.

Unpublished Papers and Books
<any? >

Nomenclature (to be included)

MARSIS = Mars Advanced Radar for Subsurface and Ionospheric Sounding

I. Introduction

<copied from the Abstract, to be streamlined>

One radar at Mars, two 20-meter long "jacks-in-the-box",three critical deployments in the middle of a successful mission: In the frame of the first European planetary mission, the deployment of the MARSIS antennas onboard the ESA Mars Express spacecraft has been itself a dedicated mission. While Mars Express was already performing regular observations at Mars, a complex process has been performed on Earth, involving the ESA Project, coordination between ESA, NASA and ASI, the Mars Science community, the spacecraft manufacturer EADS Astrium and the Mission Control Centre at ESOC.

JPL, provider of the antenna booms for the Italian instrument MARSIS, called off the deployment in April 2004, due to a newly identified risk of a boom hitting the spacecraft. Further mechanical studies and simulations took months due to the complexity of this non-deterministic problem. In parallel, finding a new deployment window had to perform a trade-off between operational constraints and science requirements of the teams who wanted to minimize the impact on the scientific coverage. Meanwhile, the MARSIS team was eager to deploy as soon as possible.

A GO for deployment was reached only in 2005. Risk analyses recommended safing measures to minimize potential impact on vital spacecraft elements and to verify its health and configuration after the deployment of each boom, which vastly increased the operational complexity. A simulations campaign in April 2005 prepared the mission team for these critical operations, while a flight pre-deployment test campaign was executed in the gaps not used by the science mission.

The first deployment firing occurred successfully on May 4th, 2005. During the subsequent precise spacecraft dynamics characterization, it was discovered that the 20-meter boom was not fully extended but bent at two thirds of its length. A strategy was developed to obtain full deployment of the boom, which was achieved thanks to a controlled warming-up by the Sun of the problematic hinge. However, this unexpected failure mode could have occurred on hinges closer to the spacecraft, which may have resulted in loss of controllability and danger to the mission.

Operations management had to trade-off between resuming the mission, antenna half-deployed and without MARSIS, on robust but inaccurate attitude controllers, or taking the risk to deploy the second long boom. At this time, and unrelated to MARSIS, a minor wheel electronics glitch occurred, during the recovery of which the spacecraft ended up on thruster control, with such poor pointing performance that communications with the spacecraft were not reliable. The anomaly was fixed "in the blind" and good communications recovered. It was decided to continue. The second 20-meter boom was successfully deployed on June 14th; the third boom, only seven meters long, on June 17th 2005. All fully extended!

2 copies to Document Review

II. Project History (1998-2004): A Radar At Mars, Why And How

This chapter describes the design and time logic that flows from the science objectives of Mars Express and Marsis to the solutions retained for constructing, mounting and deploying the booms.

Doug - Fill in Origins in RED CAPS

A. Why Marsis On-Board Mars Express

Rudi, John? ESA

B. Marsis Science Objectives Summary

Enrico? ASI

C. Antenna Design and Validation of the Deployment on Earth

← RLH portion

JPL

Richard, Doug ? JPL

D. Spacecraft Constraints

Eric? ESA - ASTRIUM

Impact on the SC attitude control during and after the deployment; resulting attitude controllers for the whole deployment phase.

Initial risk assessment

Basic requirements for characterization of the deployment

E. Operations and Commissioning Constraints

Alan M.? ESA

(also include the trade-off on the deployment target date as early / as late as possible: science demo phase for the optical instruments just after Mars arrival, concerns of the other PIs, maximum eclipse duration…)

III. Final Preparation (2004-2005): To Deploy or Not to Deploy

This chapter describes the eventful phase which transformed a No-GO in April 2004 into a Go in April 2005.

A. Overall Management and Responsibilities

Rudi, John? ESA

B. The Point of View of the Marsis Principal Investigator

Enrico?? ASI

C. Boom Deployment Studies

Richard, Doug ? JPL ← Doug A. portion

D. Spacecraft Protection Strategy

Eric? ESA - Astrium

E. Operations Coordination and In-flight Tests

Alan M.? ESA

F. Operational Timeline Preparation

Zeina? ESA

G. Preparation and Verification of Attitude Control Products

Jay, Joerg?? ESA

IV. The Deployment and Its Surprises (May-June 2005)

A. Overall Execution Conditions

Michel / Alan M.?

(usage of MCR, shifts, organization) ESA

B. The First Boom: An Excellent Spacecraft Behavior

Eric ESA - Astrium

C. The First Boom : an Unexpected Behavior

Richard, Doug ? ← RLH portion

D. Stop or Go?

Alan S. ESA

E. How to Unbend The First Boom
Mike. ESA

F. A Minor Anomaly and its Drastic Consequences
AOCS Acquisition Control Board (ACM-B) Telemetry wraparound.
Alan M.. ESA

G. The Second Boom Deployment
Michel ESA

H. The Monopole
Joerg. ESA

V. Conclusion

Michel and others

Appendix

<needed ?>.

Acknowledgments

The authors thank
<whoever we want to thank >.

References

Periodicals
<any? >

Books
<any? >

Proceedings
<any? >

Reports, Theses, and Individual Papers
<any? >

Electronic Publications
<any? >

Computer Software
<any? >

Private Communications and Web Sites
References to private communications and personal Web site addresses are generally not permitted. Private communications can be defined as privately held unpublished letters or notes or conversations between an author and one or more individuals. They *may* be cited as references in some case studies, but only with permission of the AIAA staff. Depending on the circumstances, private communications and Web site addresses may be incorporated into the main text of a manuscript or may appear in footnotes.

Unpublished Papers and Books
<any? >

Space Ops 2006.

Date: Fri, 28 Oct 2005 15:04:46 -0700
From: Document.Review@jpl.nasa.gov
Subject: Notification of Clearance - CL#05-3262
X-MIMEOLE: Produced By Microsoft MimeOLE V6.00.3790.1830
Content-class: urn:content-classes:message
Importance: normal
Thread-topic: Notification of Clearance - CL#05-3262
Thread-index: AcXcC5tuSQhIdFJKS4iEo6qk7eDzQA==
iPlanet-SMTP-Warning: Lines longer than SMTP allows found and truncated.
X-Source-IP: logistic-web.jpl.nasa.gov [137.78.111.45]
X-Source-Sender: Document.Review@jpl.nasa.gov
X-AUTH: Internal IP
Original-recipient: rfc822;rhorttor@mail.jpl.nasa.gov

The following title has been cleared by the Document Review Services, Section 274, for public release, presentation and/or printing in the open literature:

Deployment of the Marsis Radar Antennas On-board Mars Express

The clearance is CL#05-3262. This clearance is issued for the Meeting Abstract and is valid for U.S. and foreign release.

1. On the title page add the affiliation: Jet Propulsion Laboratory, California Institute of Technology.

Clearance issued by:

Adrian Segura
Document Review Services
Section 274

This email is your official Notification of Clearance; Document Review Services no longer issues hard copy clearances.

Did You Know?

Caltech, not the author, is the copyright owner of any material produced as part of the author's employment at JPL. The author does not have the power to transfer copyright.

If the publisher of your manuscript requires a transfe

Michel Denis 2/20/06

Deployment of the MARSIS Radar Antennas on-board Mars Express

M. Denis* A. Moorhouse.†, A. Smith‡, M. McKay.§
European Space Agency, ESOC, Darmstadt, Germany

J. Fischer**, P. Jayaraman††, Z. Mounzer‡‡,
VEGA, Darmstadt, Germany

R. Schmidt§§, J. Reddy***,
European Space Agency, ESTEC, Noordwijk, The Netherlands

E. Ecale†††,
EADS Astrium, Toulouse France

R. Horttor‡‡‡, D. Adams§§§,
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

and

E. Flamini****
Italian Space Agency, Rome, Italy

On the first European planetary mission, the deployment of the two 20-meter long MARSIS antennas onboard the ESA Mars Express spacecraft has represented an unprecedented technological challenge, in the middle of a successful science mission. While Mars Express was already performing regular observations at Mars, a complex process has been performed on Earth, involving the ESA Project, coordination between ESA, NASA and ASI, the Mars Science community, the spacecraft manufacturer EADS Astrium and the Mission Control Centre at ESOC. This paper describes the steps that led from an initial no-go in 2004 to deployment one year later, as well as the conditions and difficulties encountered during the actual deployment. It provides insights in the technical and managerial processes that made it a success, and analyses the rationale behind the decisions.

---

* Mars Express Mission Operations Manager, Operations Department.
† Mars Express Deputy Spacecraft Operations Manager, Operations Department.
‡ Head of the Flight Operations Division and Mars Express Flight Operations Director, Operations Department.
§ Mars Express Ground Segment Manager and Deputy Flight Operations Director, Operations Department.
** Mars Express Attitude and Orbit Control Operations Engineer, Operations Department.
†† Mars Express Attitude and Orbit Control Operations Engineer, Operations Department.
‡‡ Mars Express Data and System Operations Engineer, Operations Department.
§§ Mars Express Project Manager, Science Projects Department.
*** tbd.
††† tbd.
‡‡‡ Mars Express-NASA Project Manager
§§§ tbd.
**** tbd

Deployment of the MARSIS Radar Antennas

On-board Mars Express

M. Denis* A. Moorhouse.†, A. Smith‡, M. McKay.§
European Space Agency, ESOC, Darmstadt, Germany

J. Fischer**, P. Jayaraman††, Z. Mounzer‡‡,
VEGA, Darmstadt, Germany

R. Schmidt§§, J. Reddy***,
European Space Agency, ESTEC, Noordwijk, The Netherlands

E. Ecale††† ,
EADS Astrium, Toulouse France

R. Horttor‡‡‡ , D. Adams§§§ ,
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

and

E. Flamini****
Italian Space Agency, Rome, Italy

On the first European planetary mission, the deployment of the two 20-meter long MARSIS antennas onboard the ESA Mars Express spacecraft has represented an unprecedented technological challenge, in the middle of a successful science mission. While Mars Express was already performing regular observations at Mars, a complex process has been performed on Earth, involving the ESA Project, coordination between ESA, NASA and ASI, the Mars Science community, the spacecraft manufacturer EADS Astrium and the Mission Control Centre at ESOC. This paper describes the steps that led from an initial no-go in 2004 to deployment one year later, as well as the conditions and difficulties encountered during the actual deployment. It provides insights in the technical and managerial processes that made it a success, and analyses the rationale behind the decisions.

* Mars Express Mission Operations Manager, Operations Department.
† Mars Express Deputy Spacecraft Operations Manager, Operations Department.
‡ Head of the Flight Operations Division and Mars Express Flight Operations Director, Operations Department.
§ Mars Express Ground Segment Manager and Deputy Flight Operations Director, Operations Department.
** Mars Express Attitude and Orbit Control Operations Engineer, Operations Department.
†† Mars Express Attitude and Orbit Control Operations Engineer, Operations Department.
‡‡ Mars Express Data and System Operations Engineer, Operations Department.
§§ Mars Express Project Manager, Science Projects Department.
***tbd.
††† tbd.
‡‡‡ Mars Express - NASA Project Manager.
§§§ Senior Engineer, NASA's Jet Propulsion Laboratory.
**** tbd

Nomenclature (to be included)

MARSIS = Mars Advanced Radar for Subsurface and Ionospheric Sounding

I. Introduction

<copied from the Abstract, to be streamlined>

One radar at Mars, two 20-meter long "jacks-in-the-box", three critical deployments in the middle of a successful mission: In the frame of the first European planetary mission, the deployment of the MARSIS antennas onboard the ESA Mars Express spacecraft has been itself a dedicated mission. While Mars Express was already performing regular observations at Mars, a complex process has been performed on Earth, involving the ESA Project, coordination between ESA, NASA and ASI, the Mars Science community, the spacecraft manufacturer EADS Astrium and the Mission Control Centre at ESOC.

JPL, provider of the antenna booms for the Italian instrument MARSIS, called off the deployment in April 2004, due to a newly identified risk of a boom hitting the spacecraft. Further mechanical studies and simulations took months due to the complexity of this non-deterministic problem. In parallel, finding a new deployment window had to perform a trade-off between operational constraints and science requirements of the teams who wanted to minimize the impact on the scientific coverage. Meanwhile, the MARSIS team was eager to deploy as soon as possible.

A GO for deployment was reached only in 2005. Risk analyses recommended safing measures to minimize potential impact on vital spacecraft elements and to verify its health and configuration after the deployment of each boom, which vastly increased the operational complexity. A simulations campaign in April 2005 prepared the mission team for these critical operations, while a flight pre-deployment test campaign was executed in the gaps not used by the science mission.

The first deployment firing occurred successfully on May 4th, 2005. During the subsequent precise spacecraft dynamics characterization, it was discovered that the 20-meter boom was not fully extended but bent at two thirds of its length. A strategy was developed to obtain full deployment of the boom, which was achieved thanks to a controlled warming-up by the Sun of the problematic hinge. However, this unexpected failure mode could have occurred on hinges closer to the spacecraft, which may have resulted in loss of controllability and danger to the mission.

Operations management had to trade-off between resuming the mission, antenna half-deployed and without MARSIS, on robust but inaccurate attitude controllers, or taking the risk to deploy the second long boom. At this time, and unrelated to MARSIS, a minor wheel electronics glitch occurred, during the recovery of which the spacecraft ended up on thruster control, with such poor pointing performance that communications with the spacecraft were not reliable. The anomaly was fixed "in the blind" and good communications recovered. It was decided to continue. The second 20-meter boom was successfully deployed on June 14th; the third boom, only seven meters long, on June 17th 2005. All fully extended!

II. Project History (1998-2004): A Radar At Mars, Why And How

This chapter describes the design and time logic that flows from the science objectives of Mars Express and Marsis to the solutions retained for constructing, mounting and deploying the booms.

A. Why Marsis On-Board Mars Express

Rudi, John?

B. Marsis Science Objectives Summary

Enrico?

C. Antenna Design and Validation of the Deployment on Earth

The MARSIS antenna faced a serious design challenge: namely to produce a 40 m dipole and a 7 m monopole that fit within a modest stored volume, a tight mass constraint, and when deployed would exhibit a first mode natural frequency of at least 0.05 Hz. The solution was a tubular structure made of fiber glass layers and Kevlar composites. The dipole booms were each 20 m long and 3.8 cm in diameter. The monopole was 7 m long and 2.0 cm in diameter. The tubes were folded into 1.5 m segments at 13 hinge points made of cut outs in the tube walls. Each dipole boom was folded into a volume of about half of its uncompressed state. The resulting compressed stored energy was to become a major driver for the deployment dynamics.

The spacecraft designers worried about two mechanical aspects of the antenna. One was the tip off transient at initial deployment where the concern was dynamic shock to the spacecraft. A finite element model developed by the antenna manufacturer, Northrop Grumman - Astro Aerospace, produced the predicted shock spectrum. Spacecraft dynamics experts determined there was no threat. The second worry was the deployed natural frequency which had to be greater than 0.05 Hz in order to not interfere with spacecraft attitude control. The aforementioned finite element model together with vibration tests produced an answer of about 0.08 Hz. However, it took about a year and a half to resolve the residual concerns given the criticality of this parameter.

Meanwhile, no one worried about the approximately one minute of the actual deployment transient. Each 20 m boom had mass of 1-kg. The structure was so large and light, there was no real way to test it in Earth gravity and atmosphere. Astro Aerospace developed a simulation program to model the deployment transient. The result appeared sufficiently benign that no one actually questioned the validity of the model. In April 2004, while working with a deployment simulation of the antenna for the SHARAD instrument (SHAllow RADar, an instrument on NASA's Mars Reconnaissance Orbiter), an error in the way damping was modeled in the software was discovered. When corrections were made to the MARSIS deployment model, the results were highly chaotic and so different from the previous results that proceeding with MARSIS deployment at that time would have been irresponsible. The Mars Express-NASA Project Manager notified ESA of the need to postpone the scheduled deployment. As it happened, this realization and notification took place a mere 12 hours before ESA was to load the deployment sequence aboard the spacecraft.

The expected science value was such the deployment was very desirable. JPL spent the next four weeks attempting to identify and solve the problems. At a review with ESTEC on May 14, 2004, it became apparent that too little was actually known about the real deployment expectations and the mechanical properties to proceed. JPL then put together what amounted to a retroactive qualification effort, considering the flight article was already at Mars and only the Engineering Model was available to test. This effort will be described later.

D. Spacecraft Constraints

Eric?

Impact on the SC attitude control during and after the deployment; resulting attitude controllers for the whole deployment phase.

Initial risk assessment

Basic requirements for characterization of the deployment

E. Operations and Commissioning Constraints

Alan M.?

(also include the trade-off on the deployment target date as early / as late as possible: science demo phase for the optical instruments just after Mars arrival, concerns of the other PIs, maximum eclipse duration...)

III. Final Preparation (2004-2005): To Deploy or Not to Deploy

This chapter describes the eventful phase which transformed a No-GO in April 2004 into a Go in April 2005.

A. Overall Management and Responsibilities

Rudi, John?

B. The Point of View of the Marsis Principal Investigator

Enrico??

C. Boom Deployment Studies

One of the key issues with a lightweight, large motion, and highly dynamic deployment such as MARSIS is that friction, gravity, and aerodynamic resistance forces will dominate any attempts at ground based testing. The boom is extremely light weight and its properties are also temperature dependent. As a result of the influence of these forces it impossible to test the full system behavior prior to flight and we must rely on analysis to predict the deployment dynamics. Due to the infeasibility of a full system test, a computational study was used to determine the critical controlling parameters of the deployment which resulted in narrowing the planned component testing to three major parameters: the hinge buckling strength, the hinge torque profile, and the stowed compressive energy.

The hinge buckling strength was measured using sections of the flight spare boom in a four-point bending fixture. Results from this test indicated that the in-situ hinge strength of the flight booms was lower than previous measurements had suggested and that buckling could occur both in the hinge section and in the material immediately adjacent to the hinges. Additionally, the hinge deployment torque was measured in an environmental chamber at its on-orbit temperature of -70 C to better characterize its contribution to the deployment energy as well as the hysteresis energy dissipation associated with any hinge buckling events. Finally, the stowed energy due to the compression of the tube diameter in the cradle was measured in a vacuum chamber at -70 C for all three booms.

The boom deployments were simulated using a highly specialized ADAMS model. The model was constructed with 13 straight segments connected by spline hinge joints that reproduced the measured hinge torque profile and buckling strengths. Each of the 13 straight segments was composed of two beam elements that employed an automated algorithm to update the structural (stiffness proportional Rayleigh) damping parameter based on the local straight section beam length and end conditions. Finally, the accordion style stowed state was modeled with gap springs connecting adjacent boom segments in order to capture the stowed compressive energy.

A total of 1000 cases of the ADAMS model were run in a Monte Carlo study of the deployment dynamics. One of the key results from the Monte Carlo analysis was the discovery that a number of scenarios were possible that could result in the boom re-contacting the spacecraft during the deployment. Due to the high compressive energy the dipole boom reaches its full 20 m length in about 2.5 seconds, after which, it typically experiences a “whip” type behavior and tends to fold back towards the spacecraft in two or more sections. The margin against boom re-contact was quantified based on the closest buckled hinge after the full length of the boom was reached and it was exhibiting recoiling motion.

Results from the Monte Carlo study indicated that there was a significant probability that the MARSIS booms could contact the spacecraft or solar arrays during the deployment. Based on this result, a failure modes analysis was done at ESA using the energies and incidence angles obtained from the Monte Carlo runs. The conclusion of this analysis was that, while significant damage to the spacecraft was possible, the likelihood of it occurring was very low. Hence, the decision was made to proceed with the deployment.

D. Spacecraft Protection Strategy
Eric?

E. Operations Coordination and In-flight Tests
Alan M.?

F. Operational Timeline Preparation
Zeina?

G. Preparation and Verification of Attitude Control Products
Jay, Joerg??

IV. The Deployment and Its Surprises (May-June 2005)

A. Overall Execution Conditions
Michel / Alan M.?
(usage of MCR, shifts, organization)

B. The First Boom: An Excellent Spacecraft Behavior
Eric

C. The First Boom : an Unexpected Behavior

Having spent a year working the technical issues involved in deployment, the ESA/NASA JPL/EADS Astrium team approached the scheduled May 4, 2005 deployment with enthusiasm and confidence. At first impression of the event, deployment appeared successful. There was a significant tip off motion of the spacecraft, followed by jerky motions of the dynamics, concluding with a damped sinusoidal behavior. Champagne time at ESOC!

However, detailed analysis of the flight telemetry showed a total of three clearly observable frequencies at 0.043 Hz and 0.146 Hz about one axis and the third at 0.076 Hz about the other axis instead of the expected pair of frequencies near 0.10 Hz. These measured frequencies were completely unexpected. The moments of inertia data for the spacecraft also were not consistent with a single segment boom. The anomalous inertia cross-product values and the smaller than expected principal axis values suggested a partial deployment with a "bent" end. Both the frequency and inertial data were consistent with the 10^{th} hinge from the spacecraft being stalled at a 40° angle. An "even" numbered hinge would have been colder than an "odd" numbered hinge and would have been pre-bent away from the sun direction.

Test data taken months before on the hinge torque versus angle characteristic at very cold temperature showed a small region of negative torque at about 40°! If the boom deployment energy had reached zero with the boom segment bent greater than 40° deg at hinge-10, the segment could easily remain "stuck". Thus a 40° partially deployed hinge-10 was the likely condition. As it happened, the sun angle at that hinge was such that it gave the least possible warming , thus adding strength to the theory.

D. Stop or Go?
Alan S.

E. How to Unbend The First Boom
Mike.

F. A Minor Anomaly and its Drastic Consequences
AOCS Acquisition Control Board (ACM-B) Telemetry wraparound.
Alan M..

G. The Second Boom Deployment
Michel

H. The Monopole
Joerg.

V. Conclusion

Michel and others

Appendix

<needed ?>.

Acknowledgments

The authors thank
<whoever we want to thank >.

References

Periodicals
<any? >

Books
<any? >

Proceedings
<any? >

Reports, Theses, and Individual Papers
<any? >

Electronic Publications
<any? >

Computer Software
<any? >

Private Communications and Web Sites
References to private communications and personal Web site addresses are generally not permitted. Private communications can be defined as privately held unpublished letters or notes or conversations between an author and one or more individuals. They *may* be cited as references in some case studies, but only with permission of the AIAA staff. Depending on the circumstances, private communications and Web site addresses may be incorporated into the main text of a manuscript or may appear in footnotes.

Unpublished Papers and Books
<any? >

End of File